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RESEARCH MEMORANDUM

EFFECT OF MECHANICALLY INDUCED SINUSOIDAL AIR-FLOW OSCILLATIONS ON OPERATION OF A RAM-JET ENGINE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An experimental investigation conducted in a 16-inch ram-jet engine has shown the degree to which inlet flow pulsations influence the combustion efficiency and lean blow-out limit of a ram-jet combustor. It is shown that pulsed air flow affects combustion efficiency and lean blow-out limit depending upon flame-holder configuration, fuel-injector location, and frequency of flow pulsation.

The influence of the combustor on inlet flow pulsations is also reported. Investigation has shown that a combustor may amplify or attenuate inlet pressure pulsations. The degree to which the combustor attenuates pressure pulsations is dependent upon the flame-holder pressure-loss coefficient, while the degree to which a combustor amplifies pressure pulsations depends on the engine total-temperature ratio τ. As τ increases, the amount by which the combustor amplifies the pressure pulse also increases.

INTRODUCTION

Although a considerable amount of work has been done in developing components for supersonic ram-jet engines, and appreciable information is availabe on the thrust and efficiency of the complete engine, little is known concerning the dynamic response of the internal flow system to disturbances which may be imposed on the engine.

The source and the type of disturbance to which a ram-jet engine may be subjected are varied, the most common thus far encountered being subcritical diffuser instability, frequently called buzz. Cold-flow evaluation of a diffuser for a typical 16-inch-diameter ram-jet engine indicated buzz frequencies of the order of 20 cycles per second and amplitudes as great as 7.4 pounds per square inch or 30 percent of the combustor static pressure (ref. 1). Such flow oscillations can be expected to influence the local fuel-air mixtures in the region of the flame holder and, in turn, to affect the burner combustion efficiency (ref. 2).

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Operational ram-jet experience under subcritical diffuser operation has been varied. Some investigators have reported burner blow-out at the onset of buzz (ref. 3), others a beneficial attenuation of the cold-flow oscillation (ref. 1). It has become evident that an understanding of combustor operation under the conditions imposed by subcritical diffuser buzz is desirable for a more complete evaluation of 3224
ram-jet combustor design problems.

A preliminary investigation was therefore undertaken to study the effects of air-flow oscillations such as caused by an unstable diffuser on the combustor performance of a 16-inch-diameter ram-jet engine. Since cold-flow diffuser tests generally result in a sinusoidal pressure pattern, a mechanically induced sinusoidal air-flow pattern was imposed on the engine operating in a connected-pipe facility. The effect of variations in frequency and amplitude of the imposed pulsation on the performance of several combustor configurations was investigated. Also evaluated was the effectiveness of the combustors in attenuating or amplifying the imposed flow oscillation. The results observed are reported herein.

APPARATUS AND PROCEDURE

The test vehicle for this investigation was a 16-inch ram-jet engine, the details and installation of which are shown in figure 1. The engine was mounted in a connected-pipe setup and exhausted to the atmosphere.

Flow pulsing mechanism. - A $10\frac{3}{4}$-inch-diameter disk driven by a variable-speed motor drive was installed in the 12-inch air supply line to the engine. The disk was located 20 inches upstream of the diffuser inlet.

Flame holders. - Two general types of flame holders were investigated, a can and a V-gutter waffle-grid type. The can-combustor flame holder had a surface open area amounting to 133 percent of the combustion-chamber cross-sectional area. The can was rigidly fastened at its upstream end to the pilot burner. Spacers, which permitted relative movement between the can and the combustion-chamber wall, provided rear support for the can. Details of the can are given in figure 2(c). The cold-flow pressure-drop coefficient for the combustor was 1.5. This coefficient was based on a measured static differential pressure across the flame holder converted to total pressure, and on a dynamic pressure calculated from the engine air flow, static pressure, and combustor cross-sectional area.

A waffle-grid-type flame holder, shown in figure 2(d), was also used in this investigation. The flame holder had a blocked area of

54 percent, based on the combustor annular inlet area, and a cold-flow pressure-drop coefficient of 3. The open ends of the V-gutters measured $1\frac{1}{2}$ inches across.

Combustor configuration. - For the purposes of establishing the effect of flame-holder type and fuel-injector location, five combustor - fuel injector configurations were investigated. Pilot heat-release rate was maintained at 2 percent of total engine heat-release rate for all five configurations.

Configuration A consisted of a can combustor with dual upstream fuel-injector systems and is shown in figure 2(a). Six nozzles rated at 0.5 gallon per minute at a differential pressure of 100 pounds per square inch were located along the centerbody wall, and 16 nozzles rated at 0.36 gallon per minute at the same pressure differential were located midway across the annular air passage. Both sets of nozzles were approximately 17 inches upstream of the leading edge of the combustor.

Configuration B consisted of a can combustor with dual fuel-injection systems and is shown in figure 2(b). The primary fuel injector was located internal to the combustor and in the first one-sixth of the combustor length, while the secondary injectors were located midway across the annular air passage on the same axial plane as the primary injectors. The primary nozzles are described in figure 2(c). The secondary injectors consisted of simple orifices on the ends of spray bars.

Configuration C consisted of a can combustor with dual fuel-injection systems internal to the combustor and is shown in figure 2(c). Details of the nozzle sizes and locations are given in figure 2(c).

Configuration D consisted of a waffle-grid flame holder with a single fuel-injection system and is shown in figure 2(d). Sixteen nozzles rated at 0.36 gallon per minute at a differential pressure of 100 pounds per square inch were located 17 inches upstream of the flame holder and 1 inch from the centerbody wall.

Configuration E consisted of a waffle-grid flame holder with dual fuel-injection systems and is shown in figure 2(d). The fuel-injector arrangement is the same as that of configuration A.

Fuel. - The properties of the fuels clear gasoline and MIL-F-5624A, grade JP-4 are given in table I. Clear gasoline was used as pilot fuel and JP-4 fuel was used for the main burner.

Transient pressure instrumentation. - Wall static pressures were recorded at three pressure stations along the engine: diffuser inlet, diffuser exit, and combustor. The combustor pressure station was

maintained 6 inches downstream of the flame holder. The distances between pressure stations are shown in figure 1 for the can combustor; for the waffle-grid flame holder, the distance between the diffuser-exit pressure station and the combustor station was 20 inches. Pressures were recorded by diaphram-type pickups operating on an unbonded strain gage and were accurate within 1 percent of full-scale range. The strain-gage signals were recorded on strip charts of a recording galvanometer-type instrument, accurate within 2 percent of full-scale range. 3224

Operating conditions. - The ram-jet combustor was operated at the following conditions:

Inlet-air static pressures, in. Hg abs 54-33
Inlet-air temperature, $^{\circ}F$ 160
Inlet-air velocity based on engine cross-sectional area,
ft/sec 150-260

These operating conditions were chosen because experience has shown that high burner-inlet velocities coupled with low inlet temperatures present a combustor condition in which the operational characteristic of the combustor is marginal and therefore more readily affected by pulsed engine air flow.

The following table presents the frequency and amplitude conditions imposed on the engine air flow during engine operation. Range of amplitudes of the pulsed flow is presented at each static-pressure station and for each pulse frequency investigated:

Static-pressure station	Pressure pulse amplitude range, in. Hg abs	Pressure pulse frequency, cycles/sec
Diffuser inlet	9.1 - 10.9	15
	2.7 - 10.5	20
	6.4 - 10.5	25
	8.7 - 10.8	30
	13.7 - 16.0	39
	17.3	49
Combustor inlet	12.4 - 14.3	15
	5.9 - 13.7	20
	10.4 - 11.4	25
	10.3 - 13.3	30
	11.2 - 12.2	39
	9.8	49
Combustor outlet	6.8 - 13.4	15
	3.6 - 12.8	20
	6.6 - 11.4	25
	9.2 - 12.0	30
	9.2 - 10.7	39
	11.1	49

Combustion efficiency. - Combustion efficiencies were determined from a heat-balance system similar to the method outlined in reference 4. Combustion efficiency is defined as the ratio of the enthalpy change of fuel, air, quench water, and engine cooling water to the heating value of the fuel input.

RESULTS AND DISCUSSION

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The effects of pulsing air flow upon combustion efficiency and lean blow-out limit of the can and grid flame holder - combustor configurations are presented in the following discussion. For a number of the cases presented, a lean blow-out limit was never reached; lean-fuel-air-ratio operation of the engine was limited by the inability of the heat balance to measure combustion efficiency accurately at the lean fuel-air ratios. In all cases, rich operation was restricted by the capacity of the water-spray system.

Combustion Efficiency and Lean Limits

Because pressure pulsations have already been shown (ref. 2) to influence the fuel-air distribution and thus the combustion efficiency of an engine, it was anticipated that varying the fuel-injector location radially and longitudinally would vary the degree to which pulsed air flow would influence the operation of a combustor. The following discussions indicate the results of pulsed flow and variation in fuel-injector location on the operation of the two combustor types.

Dual upstream fuel injection; can combustor. - The results of pulsed air flow upon the operation of configuration A are shown in figure 3(a) and compared to the same configuration with steady flow. It is seen that pulsed flow, with upstream fuel injection, produced a shift in the lean blow-out limit and a decrease in combustion efficiency at lean fuel-air ratios. A decrease in combustion efficiency at a pulsed air-flow frequency of 20 cycles per second and an average pressure amplitude of 9.0 inches of mercury was noted below fuel-air ratios of 0.0275. This decrease in combustion efficiency at lean fuel-air ratios was probably due to an increase in fuel spreading as a result of the pulsed flow. If the mixing of fuel and air is controlled mechanically, as in reference 2, the effects of pulsed air flow on fuel spreading would be minimized. Increased fuel spreading reduces the local fuel-air ratio surrounding the pilot and therefore, according to reference 2, results in lowered combustion efficiency. Pulsed flow at fuel-air ratios greater than 0.0275, on the other hand, permitted combustion efficiencies equal to those obtained with steady flow. The dip in the efficiency curve for steady-flow combustion was attributed to fuel scheduling between the two sets of fuel injectors, whereas with pulsed flow the shift in fuel distribution reduced the effect of fuel scheduling.

The lean blow-out limit was increased from a fuel-air ratio of 0.087 for steady flow to 0.0152 for pulsed flow.

Internal and secondary fuel injection on same axial plane; can combustor. - By relocating the fuel injectors to a station closer to the flame holders and thereby shortening the fuel preparation time, it was anticipated that the combustion efficiency with pulsed air flow would 3224
be similar to that with steady flow with the same fuel-injector configuration. This was borne out with configuration B as shown in figure 3(b). The combustion efficiency with pulsed flow was equal to or greater than that with steady flow over the entire range of combustor operation. The improved combustion efficiencies indicate that pulsing flow actually improves the fuel-air mixing in the combustion zone especially at rich-fuel-air-ratio operation. Variation in frequency and amplitude (20 to 30 cps and 7.2 to 10.4 in. Hg) had little effect on combustion efficiency. There was no establishment of a lean blow-out limit for either pulsed or steady flow for this configuration.

Internal fuel injection; can combustor. - The trend established with configuration B indicated that pulsing engine air flow might have the least effect on combustion efficiency if a completely internal fuel-injection system were employed with the can combustor such as in configuration C. However, the results observed with configuration C (fig. 3(c)) were generally similar to configuration B. The combustion efficiency with pulsed flow for two values of frequency and pressure amplitude (20 and 49 cps, 9.8 and 7.95 in. Hg) was equal to or greater than that for steady flow and the same injector configuration over the entire range of engine fuel-air ratios. As with the previous configuration, no lean blow-out limit was determined for configuration C.

Upstream fuel injection; grid-type flame holder. - The second type of combustor configuration investigated consisted of a waffle-grid, V-gutter flame holder with upstream fuel injection near the centerbody wall. With this configuration, pulsed flow produced a shift in the lean blow-out limit of the engine but did not affect the combustion efficiency. The results of investigation with this configuration D are shown in figure 3(d). The lean blow-out limit was increased from a fuel-air ratio of 0.0235 for steady flow to 0.028 for pulsed flow with a frequency of 20 cycles per second. At a still higher frequency of 45 cycles per second, the lean limit shifted to a fuel-air ratio of 0.0305.

Dual upstream fuel injection; grid-type flame holder. - Previous investigation (ref. 2) has shown an extension in the lean operating range of a gutter-type flame holder through the use of a dual fuel-injection system. A similar fuel injection system was employed with this waffle-grid flame holder and the results are shown in figure 3(e). No appreciable change in combustion efficiency between pulsed and steady flow was observed, nor was the lean blow-out limit found for either type of flow.

The effect of fuel volatility on the performance of a combustor with pulsing flow was also investigated with the waffle-grid flame holder and the results are shown in figure 3(e). The fuel employed was clear gasoline. No variation in combustion efficiency was observed between the more volatile clear gasoline and the JP-4 fuel.

Combustor Influence on Engine Pressure Pulse

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Earlier observations have led to the postulation that engine combustors may possibly amplify or attenuate inlet flow pulsations, depending upon the type of combustor, the inlet parameters, and the fuel-air-ratio region in which the combustor is operating. Results obtained in this investigation confirm the postulate and also help to define the type and degree of influence exerted by the combustor on pressure disturbances in the engine. The following discussions are intended to present results that are only preliminary in nature.

Pressure amplitude coefficient. - A combustor may amplify or attenuate a pressure disturbance depending upon the engine total-temperature ratio τ; an illustration of this dependency on engine τ is shown in figure 4. In this figure, a pressure amplitude coefficient $\Delta p/p$, which is defined as the ratio of the amplitude of the static-pressure pulse to the mean local static pressure, is traced through the engine and particularly through the combustor for three values of τ. For τ of 2.20, the pressure amplitude coefficient decreased across the combustion zone; while at τ of 4.77, the pressure amplitude coefficient increased across the combustor. At τ of 3.64 (amplification ratio of 1.0), the pressure amplitude coefficient remained essentially constant through the combustor.

Combustor amplification ratio. - As a further illustration of the amplifying-attenuating qualities of a combustor with variation in τ, the ratio of pressure amplitude coefficients downstream to those upstream of the combustor are presented in figure 5 as a function of τ. This ratio is defined as the combustor amplification ratio and is an indication of the effectiveness of a combustor in amplifying or attenuating a pressure pulse passing through the engine. Amplification ratios of 1.0 or less indicate that the pressure disturbance is attenuated by the combustor while ratios greater than 1.0 mean the combustor amplifies diffuser pressure disturbances.

The combustor amplification ratios for the two flame holders tested are shown in figure 5 as a function of engine total-temperature ratio τ. These two flame holders were utilized in this investigation because they represent the two general types of flame holders currently employed in ram-jet engines and because their cold-flow pressure-loss coefficients differ significantly (1.5 and 3.0); for it was anticipated

that the greater the difference in flame-holder cold-flow pressure-loss coefficients, the greater the difference in the attenuating effect of the combustors. This assumption was proved true by the investigation and is shown in figure 5. From the figure it is seen that the waffle-grid flame holder, with its pressure-loss coefficient of 3, demonstrated a greater tendency to attenuate engine pressure pulses than a can combustor with a $\Delta P/q$ of 1.5. As an example, at τ of 3.64, the waffle-grid flame holder demonstrated an amplification ratio of 1.0 (neither amplifies nor attenuates) with a 20-cycle-per-second pulse in the engine, while the can flame holder demonstrated an amplification ratio of 1.46 3224
for the same pulse frequency and τ.

The ability of a combustor to attenuate pressure pulses is also dependent upon the frequency of the pulsations. This is seen from figure 5 by comparing the dashed line representing 15-cycle-per-second pulsations and waffle-grid flame holder with the solid line representing the waffle-grid flame holder and 20 cycles per second. It appears that over the range of τ investigated the combustor attenuation is greater at 15 cycles per second than at 20 cycles per second.

Finally, in figure 5 it is shown that the combustor amplification ratio increases with increasing engine total-temperature ratio τ. This trend in amplification ratio with τ is consistent for both flame holders. A probable explanation for the increase in amplification ratio with τ lies in the fact that each pressure pulse arriving at the combustor has added to it a pressure increment resulting from an increased combustion reaction rate associated with passage of the pressure pulse through the combustor. Increase in τ therefore increases the pressure increment and consequently the amplification ratio. However, at lower τ (below 3.64 for waffle-grid flame holder), the pressure increment due to increased burning rate is smaller than the pressure loss due to flame-holder friction, and therefore the combustor attenuates rather than amplifies the pressure pulses.

Typical pressure traces from which the values of amplitude, frequency, and static pressure were obtained are shown in figure 6. A 60-cycle-per-second trace is shown for comparison.

SUMMARY OF RESULTS

The results of mechanically induced pressure pulsations upon two flame-holder configurations in a 16-inch ram-jet engine can be summarized as follows:

1. The degree of influence of pulsed engine air flow on the combustion efficiency and lean blow-out limit of a ram-jet engine was found to vary with combustor configuration and fuel-injector location. The greater

the opportunity for fuel-air mixing upstream of the flame holder, the greater the effect of pulsed air flow on the combustion efficiency and lean blow-out limit. In general, variations in frequency from 15 to 49 cycles per second were found to have negligible effect on combustion efficiency, but some effect on the lean blow-out limit.

2. The ability of a combustor to attenuate a diffuser-induced flow oscillation increased with the flame-holder pressure-drop coefficient.

3. The tendency of a combustor to amplify engine pressure disturbances increased with increasing engine total-temperature ratio τ. As an example, a waffle-grid flame holder amplified engine pressure disturbances at τ values of 3.6 and greater; on the other hand, it damped the disturbances when τ was less than 3.6.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 26, 1953

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2. Cervenka, A. J., and Dangle, E. E.: Effect of Fuel-Air Distribution on Performance of a 16-Inch Ram-Jet Engine. NACA RM E52D08, 1952.

3. Stoolman, Leo, and Francis, Donald L.: Supersonic Diffuser Performnace With and Without Combustion. JPL Preprint, Jet Prop. Lab., C.I.T., Sept. 18, 1950.

4. Cervenka, A. J., and Miller, R. C.: Effect of Inlet-Air Parameters on Combustion Limit and Flame Length in 8-Inch Diameter Ram-Jet Combustion Chamber. NACA RM E8C09, 1948.

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TABLE I. - SPECIFICATIONS AND ANALYSIS OF PRIMARY ENGINE FUELS

MIL-F-5624A GRADE JP-4 AND CLEAR GASOLINE

	Specifications MIL-F-5624A, JP-4	Analysis	
		MIL-F-5624A, JP-4	Clear gasoline
A.S.T.M. distillation D 86-46, °F			
Initial boiling point		140	110
Percentage evaporated			
5		199	137
10	250 (max.)	224	154
20		250	178
30		270	200
40		290	218
50		305	235
60		325	250
70		352	265
80		384	284
90		427	305
Final boiling point	550 (max.)	487	358
Residue, percent	1.5 (max.)	1.2	1.3
Loss, percent	1.5 (max.)	0	1.4
Specific gravity	0.747 (min.), 0.826 (max.)	0.765	0.716
Reid vapor pressure, lb/sq in.	2.0 (min.), 3.0 (max.)	2.7	6.7
Hydrogen-carbon ratio		0.169	0.182
Net heat of combustion, Btu/lb	18,400 (min.)	18,700	18,925

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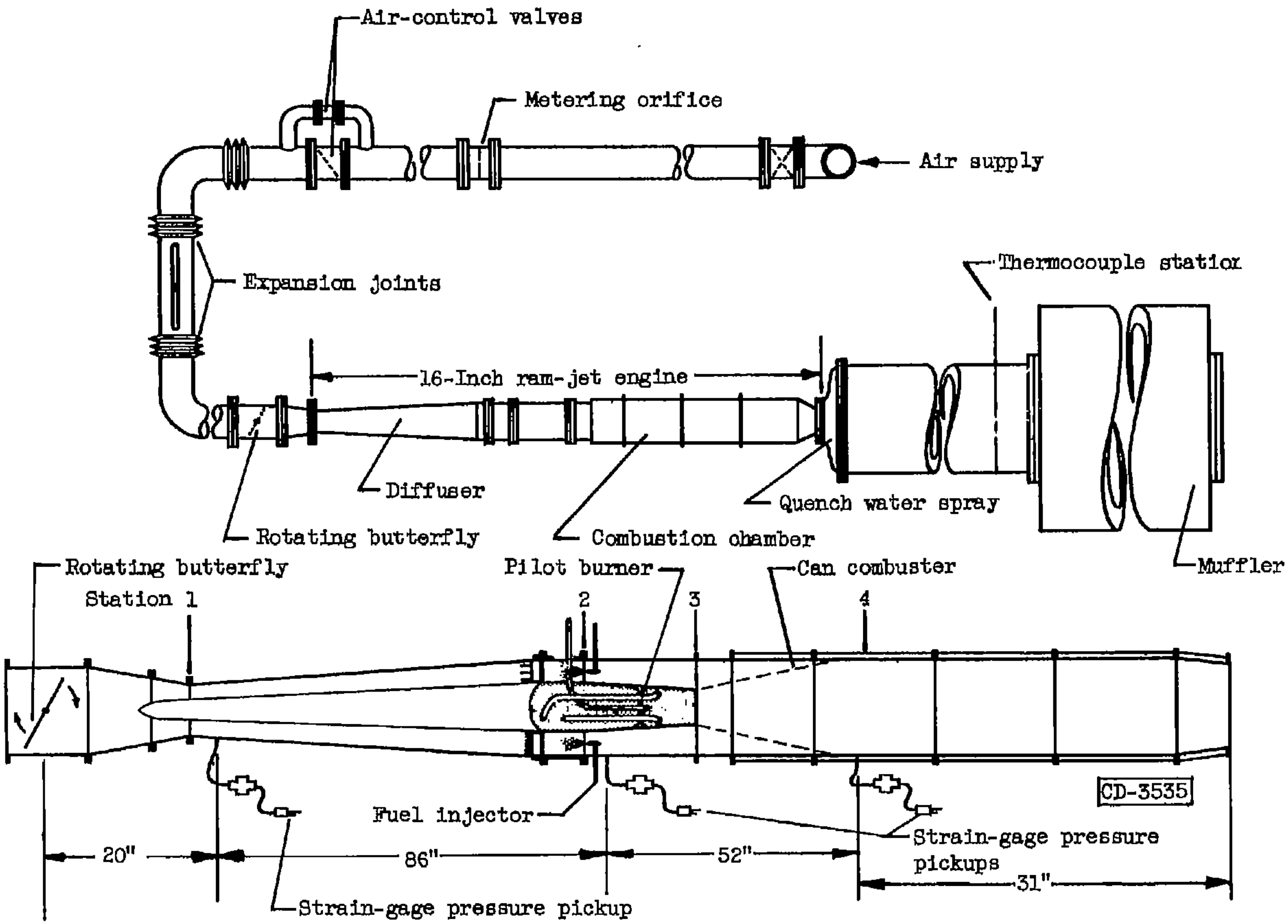

Figure 1. - Installation and details of 16-inch ram-jet engine.

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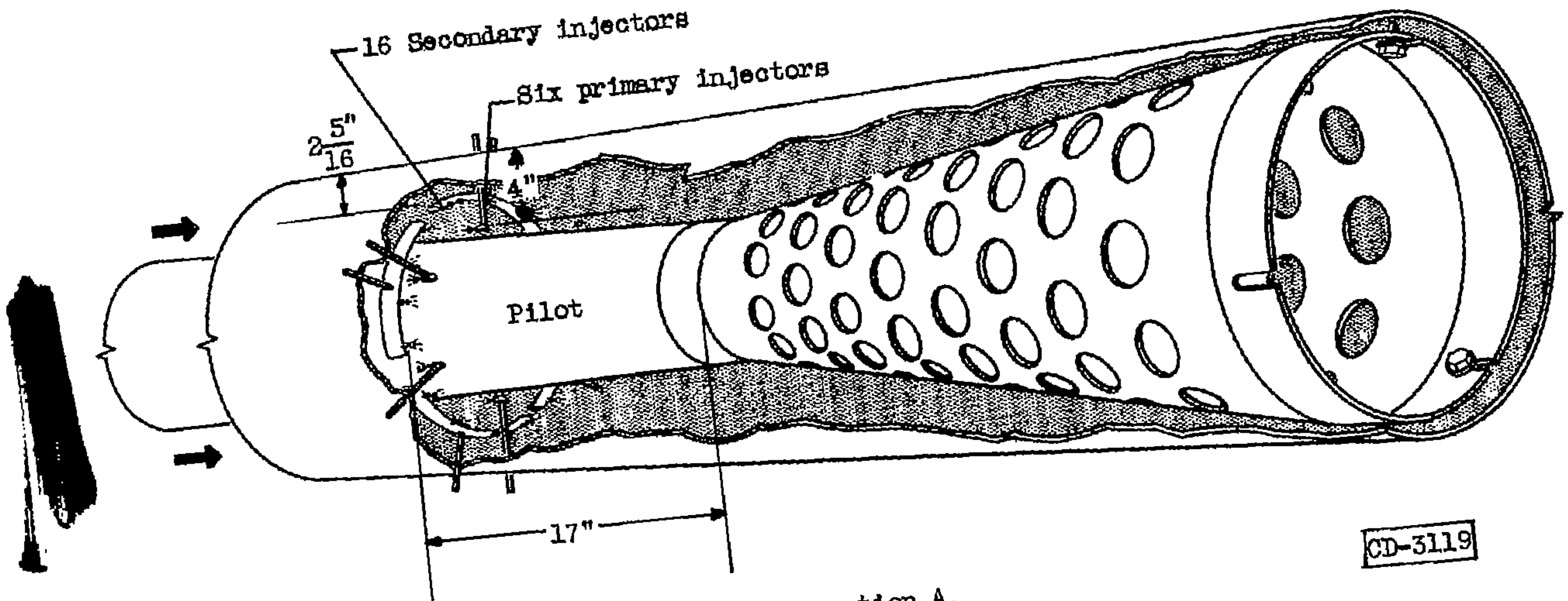
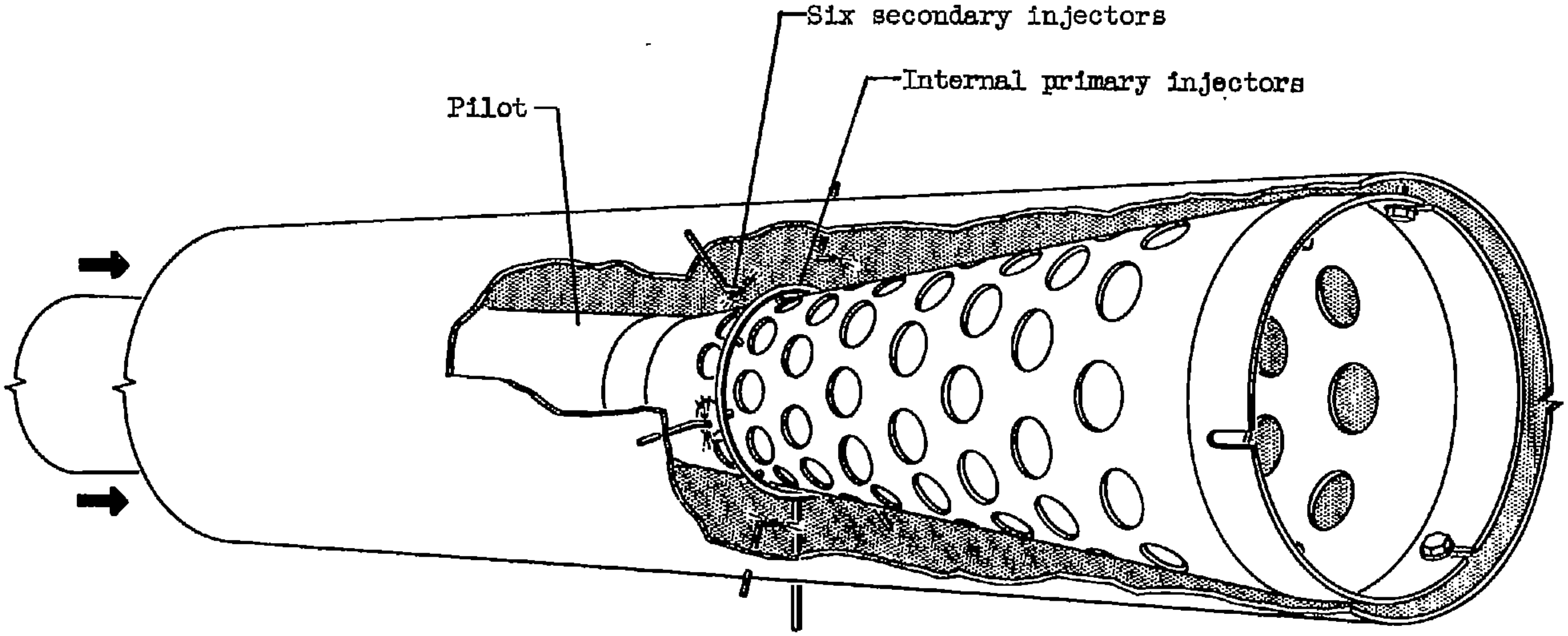


(a) Configuration A.

Figure 2. - Combustor configurations.



(b) Configuration B.

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Figure 2. - Continued. Fuel-injector configurations.

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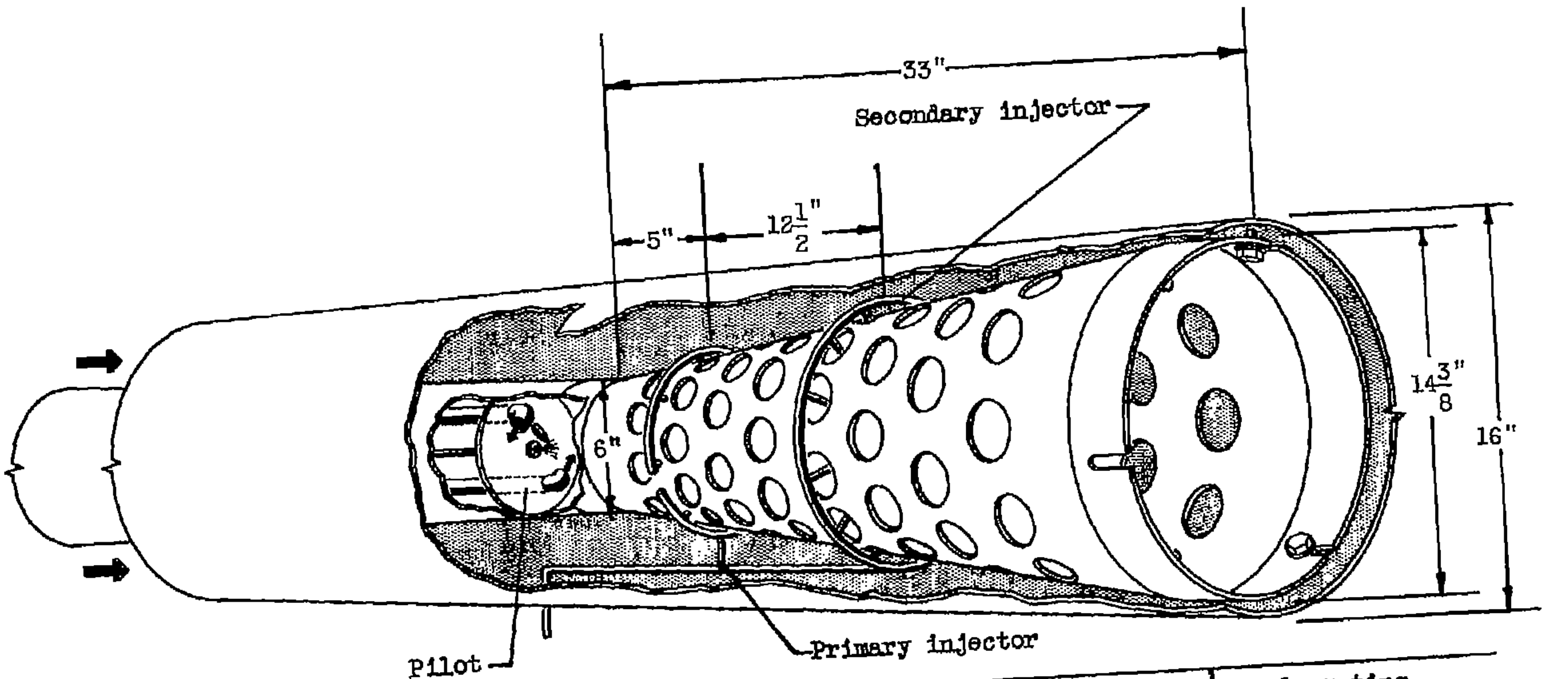

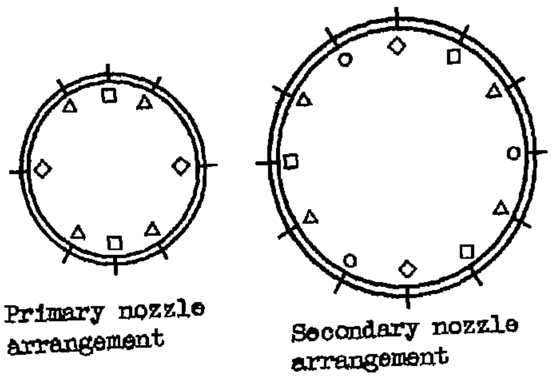

Nozzle spray	Spray direction	Nozzle rating at 100 lb/sq in., gal/min	
		Primary manifold	Secondary manifold
○ Conical	Radial	0.667	1.000
□ Conical	45° Upstream		
◇ Conical	45° Downstream		
△ Flat	Downstream	.625	0.625

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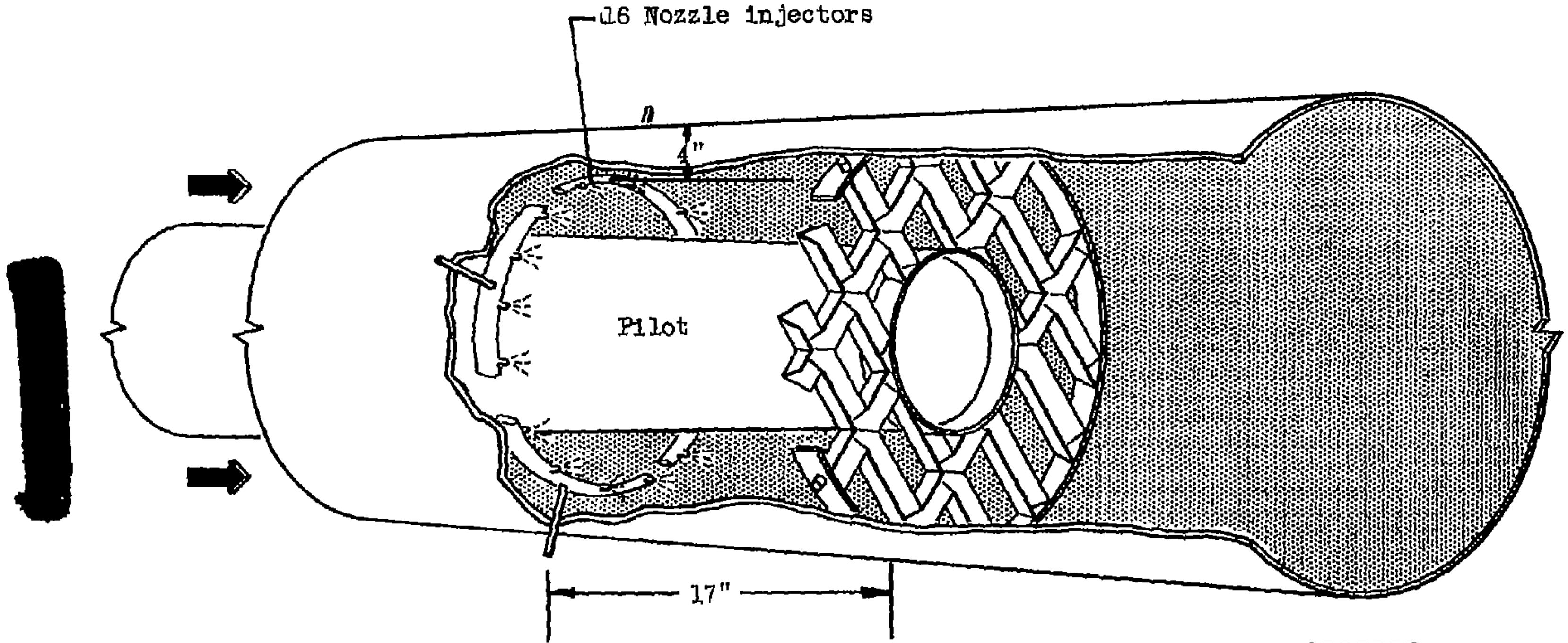
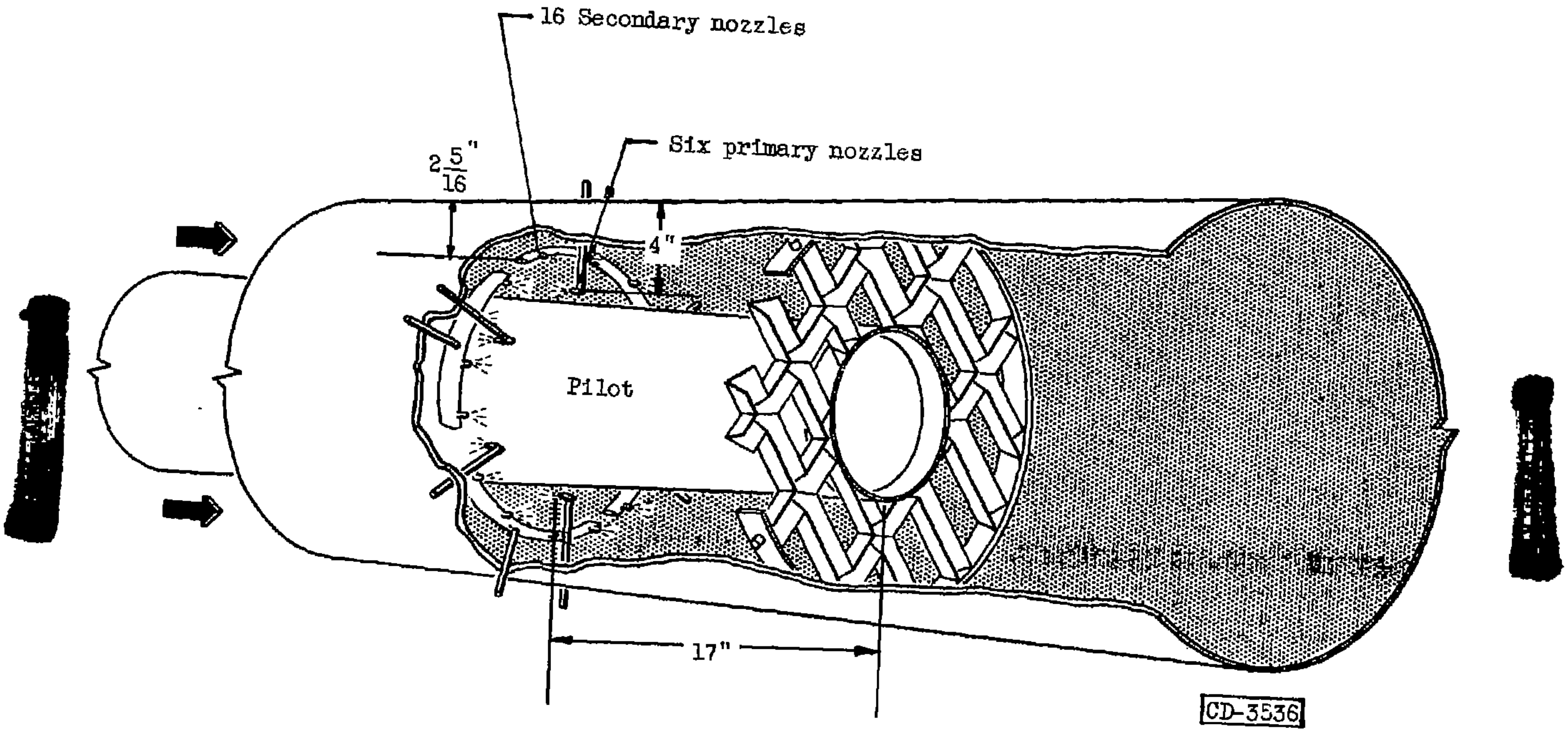
(c) Configuration C.

Figure 2. - Continued. Combustor configurations.



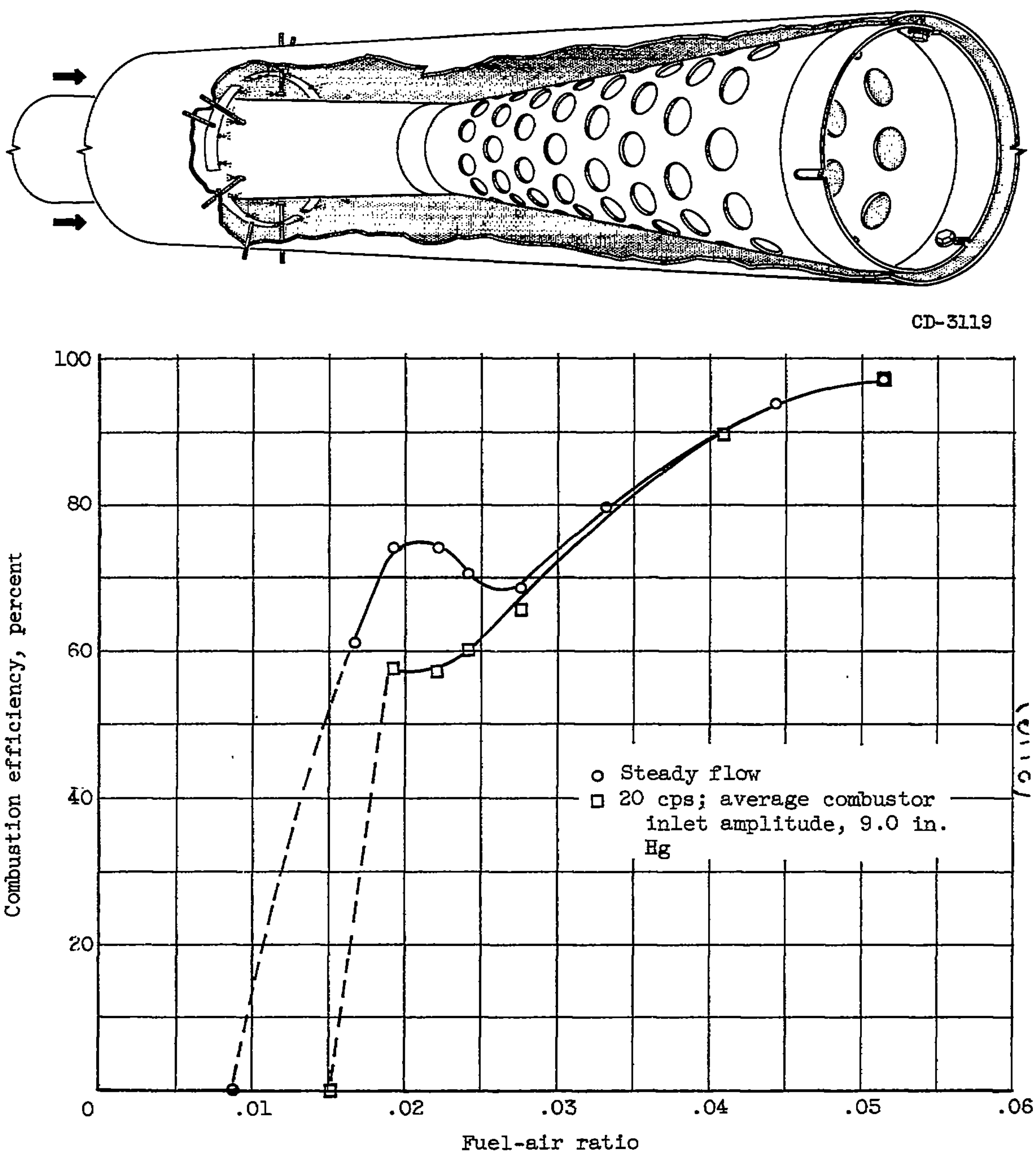
(d) Configuration D.

Figure 2. - Continued. Combustor configurations.



(e) Configuration E.

Figure 2. - Concluded. Combustor configurations.



(a) Configuration A. Primary fuel-air ratio, 0.02; combustor-inlet static pressure, 37 to 51 inches of mercury absolute.

Figure 3. - Combustor performance with and without pulsed engine air flow. Inlet-air temperature, 160° F; velocity, 150 to 260 feet per second.

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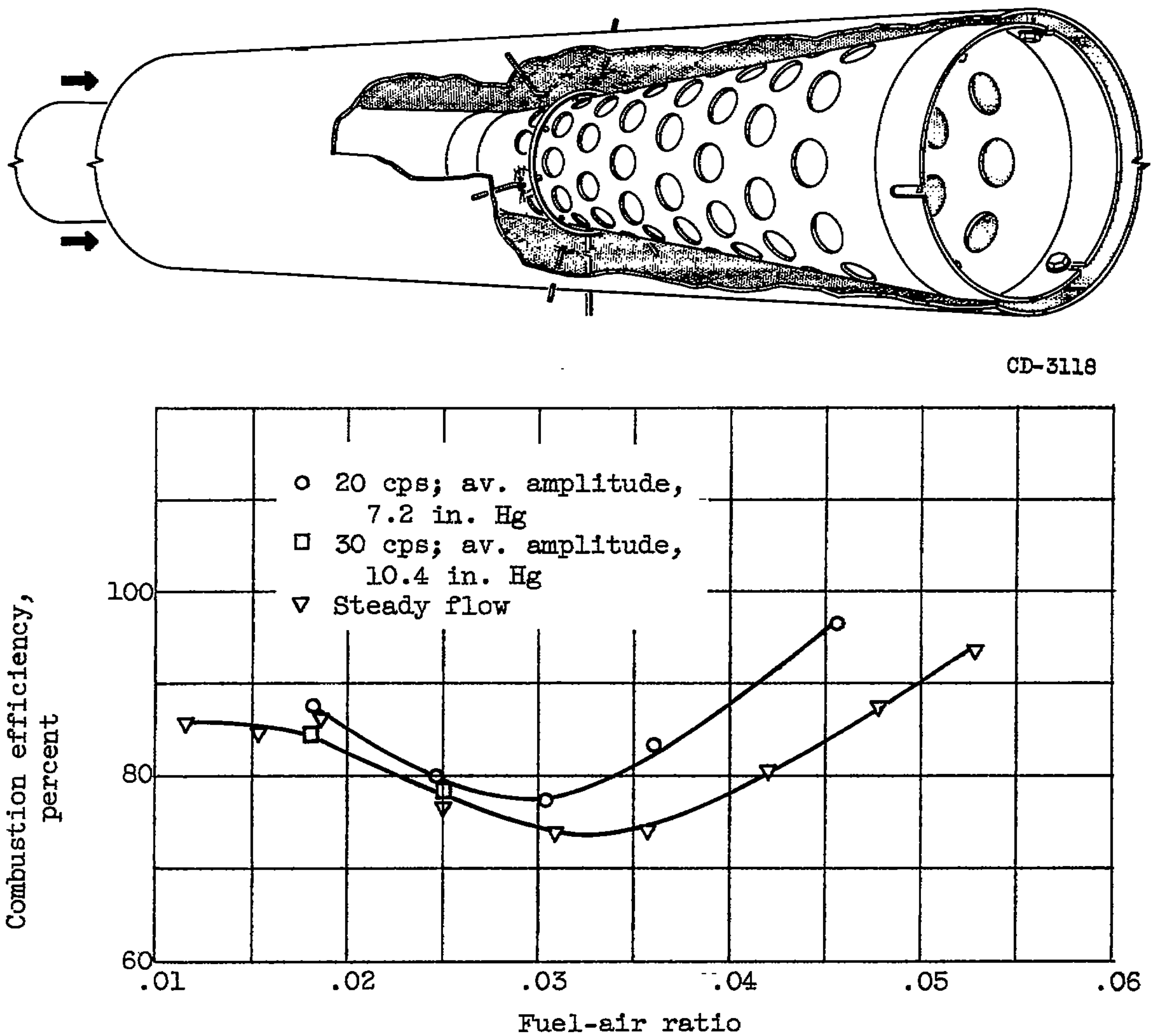

(b) Configuration B. Primary fuel-air ratio, 0.018; combustor-inlet static pressure, 37 to 46 inches of mercury absolute.

Figure 3. - Continued. Combustor performance with and without pulsed engine air flow. Inlet-air temperature, 160° F; velocity, 150 to 260 feet per second.

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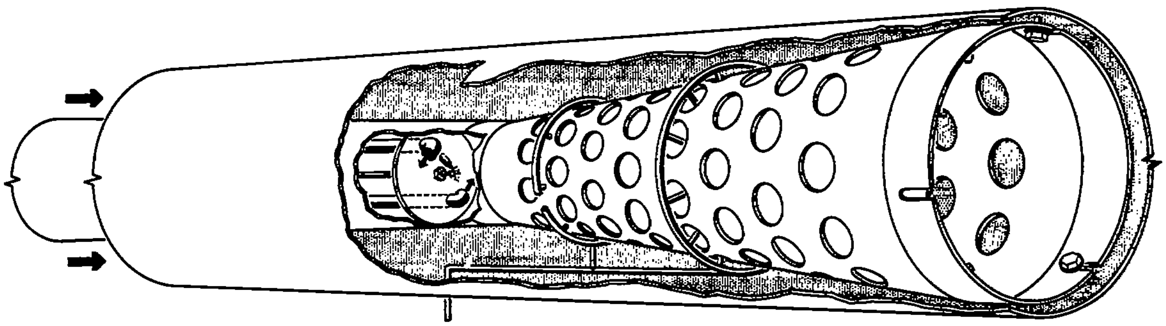

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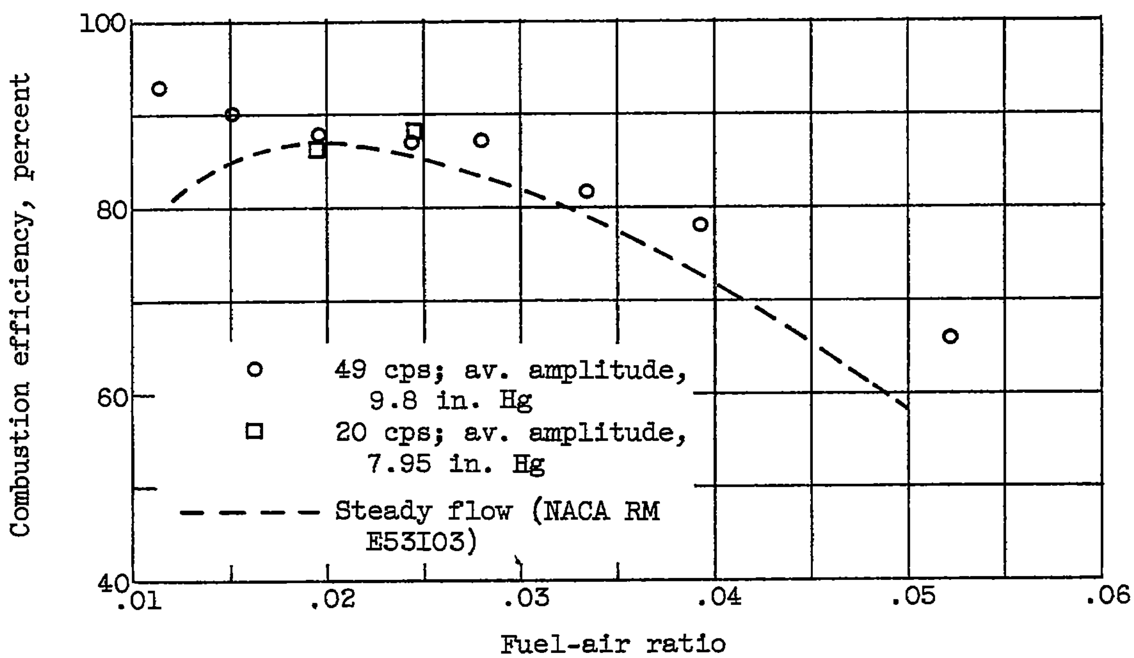

(c) Configuration C. Primary fuel-air ratio, 0.025; combustor-inlet static pressure 35 to 40 inches of mercury absolute.

Figure 3. - Continued. Combustor performance with and without pulsed engine air flow. Inlet-air temperature, 160° F; velocity, 150 to 260 feet per second.

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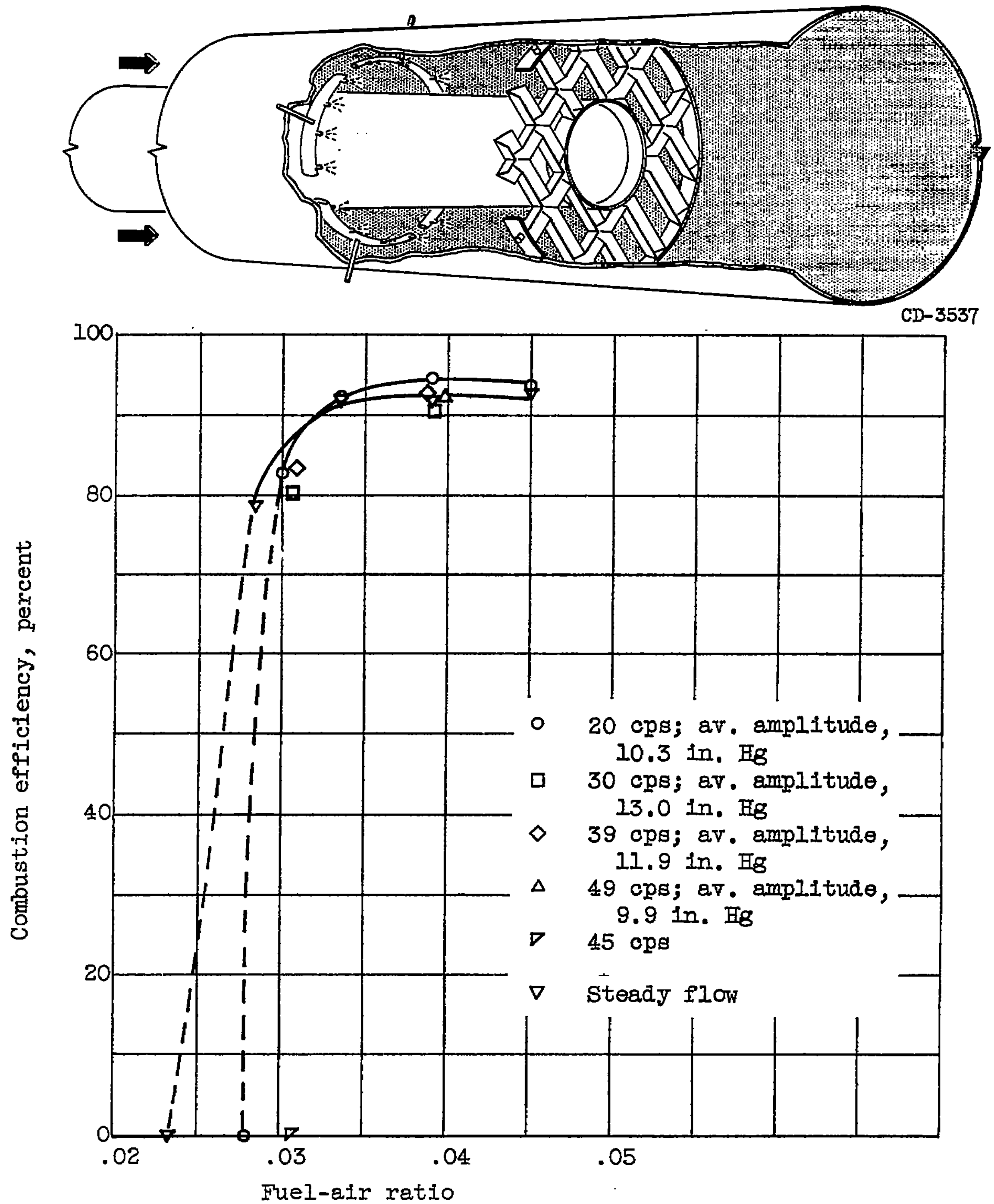

(d) Configuration D. Combustor inlet-static pressure, 43 to 48 inches of mercury absolute.

Figure 3. - Continued. Combustor performance with and without pulsed engine air flow. Inlet-air temperature, 160° F; velocity, 150 to 260 feet per second.

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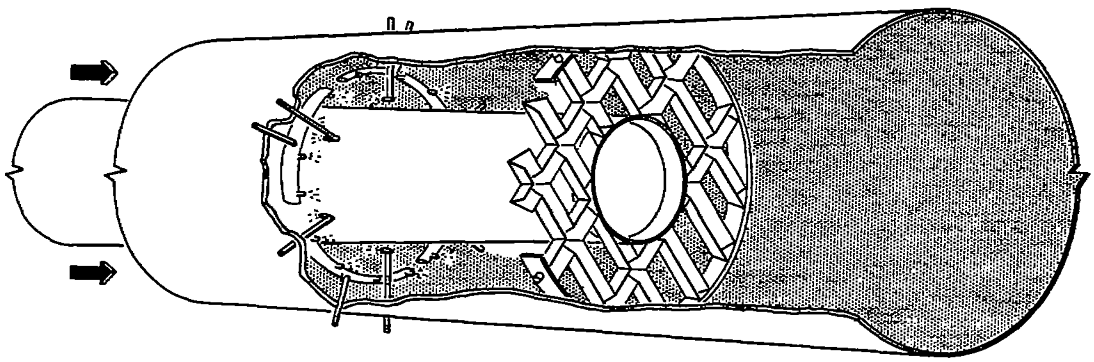

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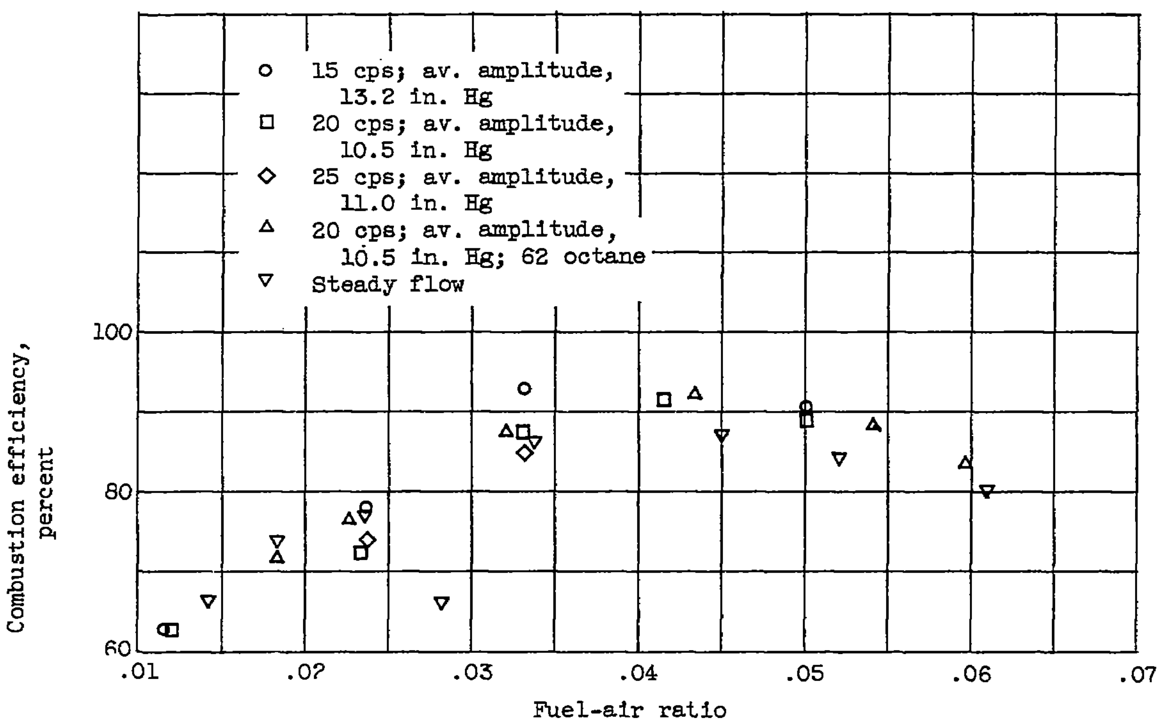

(e) Configuration E. Primary fuel-air ratio, 0.02; combustor-inlet static pressure, 37 to 49 inches of mercury absolute.

Figure 3. - Concluded. Combustor performance with and without pulsed engine air flow. Inlet-air temperature, 160° F; velocity, 150 to 260 feet per second.

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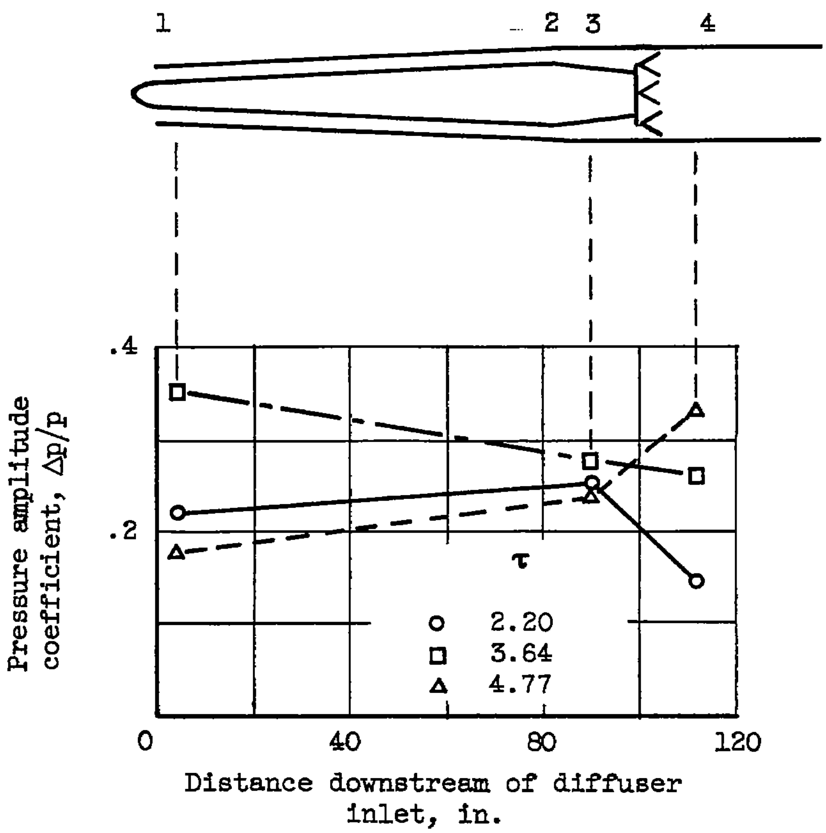

Figure 4. - Variation in pressure amplitude coefficient through 16-inch ram-jet engine with engine total-temperature ratio τ. Waffle-grid-flame holder.

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